HEWLETT-PACKARD COMPANY II (A)

Mechanical Design of a Rotary Vane Microwave Attenuator

Stephen Adam works for Hewlett-Packard, one of the country's largest manufacturers of laboratory instruments. Although he was educated as a mechanical engineer, his work has led him into microwave[1] engineering. In January, 1962, Mr. Adam began environmental tests on a "rotary vane waveguide attenuator" he had designed. He estimated that it would take at least three months for the instrument to progress from the prototype stage through pilot runs into final production.

The new attenuator could regulate microwave power far more precisely than any other attenuator made by Hewlett-Packard or its competitors. The marketing department believed that demand for the attenuator would be great. Hewlett-Packard therefore hoped to have it ready for display at the March IEEE convention, at which the company annually displayed its new products to potential customers. Slightly less than three months before the convention, some prototype castings cracked during environmental testing.

[1] A microwave is an electromagnetic wave having length between 30 cm and 1 mm.

Prepared in the Design Division, Department of Mechanical Engineering, Stanford University by Eugene Echterling, revised by Sue Hays April, 1967, under the direction of Professor Peter Z. Bulkeley as a basis for student exercises. The cooperation of Stephen Adam and Cliff Seymour of the Hewlett-Packard Company is gratefully acknowledged.

Attenuation

Microwave power may be regulated by placing a movable resistive element in the wave path. Any component of the electric field which lies in the plane of the resistive element produces currents in the element. These currents transform the component's energy into heat, thereby attenuating the wave.[1]

Design

Each of the three sections composing Mr. Adam's attenuator contained a longitudinally oriented resistive element (fig.1). These elements were thin, nickel-chromium films vacuum-deposited onto mica cards. The resistive element in the center section was to be sandwiched between two plastic half-cylinders (fig. 2). An external gear drive (not shown in figure 1) was to vary the attenuation by rotating the entire center section.[2] The end section cards were to eliminate electric field components not parallel to the short side of the wave guide, thereby "straightening out" the electric field again.

Mr. Adam designed the center section in one piece. This reduced machining and assembly costs, eliminated misalignment problems, and prevented power loss through cracks. The tube was an aluminum sandcasting shown in Exhibits II and III. Two lengthwise slots, which were to be filled with polyiron[3], were cast diametrically opposite one another on the inside of the tube. Mr. Adam calculated what the slot depth should be from theoretical considerations. He believed the slots essential in dissipating the power of certain unwanted waves propagated in the center section. After the mixture in the slots hardened, the tube was "gun drilled" to its final dimension. The residual machining roughness of 63 micro-inches provided a good frictional grip between the casting and its plastic core insert.

[1] Exhibit I is an exerpt from the Hewlett-Packard Journal which describes how the rotary vane attenuator works.

[2] Attenuation would be zero, for example, if the section were rotated so that the resistive card would be perpendicular to the electric field.

[3] Polyiron is a mixture of powdered iron and epoxy resin.

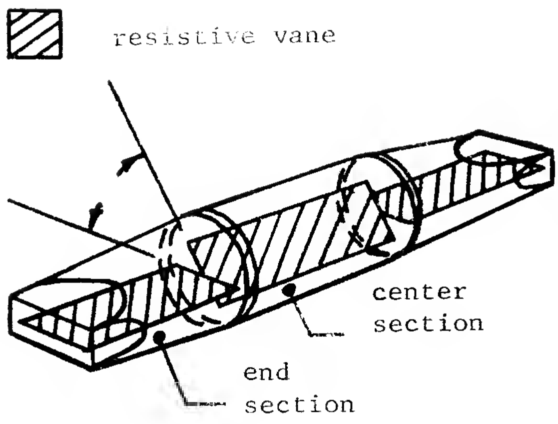
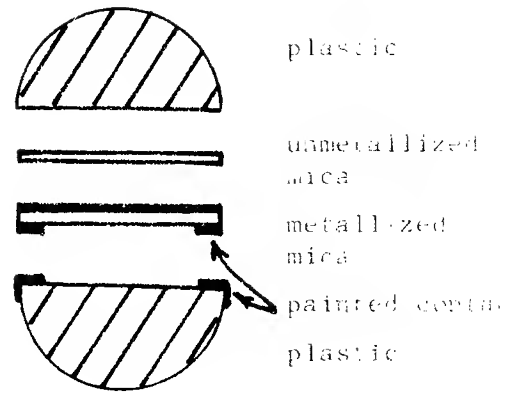


Figure 1
general configuration of rotary
vane attenuator



[illegible] view of center core asse[illegible]

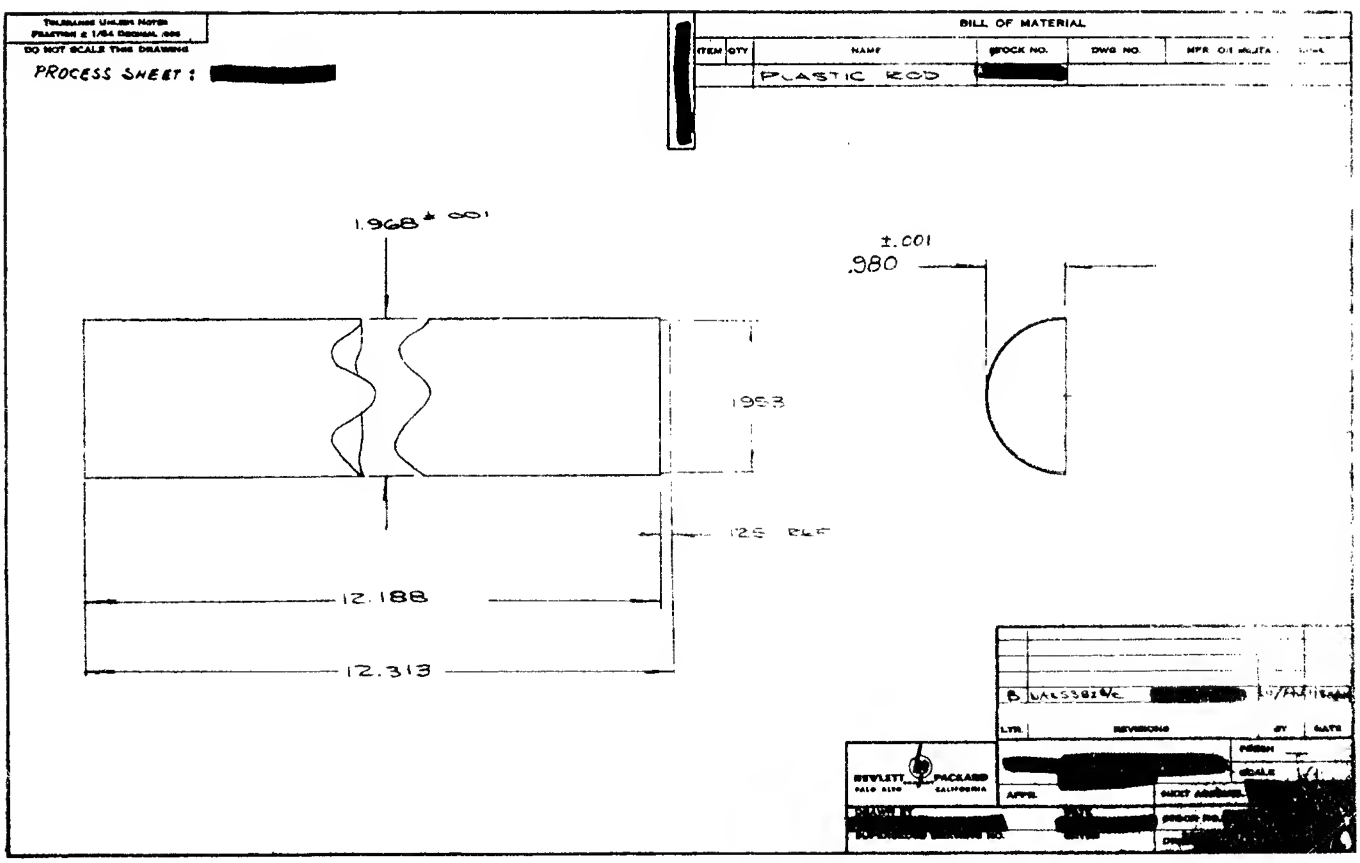


Figure 3
machine drawing of plastic sem[illegible] cylinder

Corė construction

To center the resistive film in the casting bore, two mica cards of equal thickness were placed between identical half-cylinders (figures 2 and 3). Only one of the cards was metallized. It was placed with its metallic surface against the other card.

To assure electrical contact with the aluminum wall, both the metallized card and the adjacent plastic were coated with metallic paint along their long edges. These edges, which were in contact with the aluminum tube, also conducted heat away from the mica.

Each plastic half-cylinder was cut from a turned plastic rod. Since it was impossible to slit a rod into halves both of which fell within the required tolerances, half of each rod had to be scrapped.

Assembly

The assembly procedure[1] involved: 1) cooling the plastic and mica sandwich (held together with rubber bands) in a liquid nitrogen bath, 2) slipping the aluminum casting -- which was still at room temperature and thus larger in diameter than the contracted plastic -- over the sandwich, and 3) allowing the assembly to warm to room temperature, producing a shrink fit. The assembly had to be aligned immediately upon removal from the liquid nitrogen because condensed water vapor would freeze the parts together after about two minutes. Freezing would occur before the assembly expanded enough to produce a shrink fit. The assembly was then cut to final length on a lathe.

Fit

During shipment, the instrument might be exposed to temperatures ranging from -40° to +75°C. Consequently, the fit had to be tight at -40°C yet not rupture the casting at +75° C. Judging from past experiences with interference fits, Mr. Adam estimated that the following diametrical interferences (at room temperature) would be satisfactory: 1) 0.006 to 0.010 inches along the mica cards, 2) 0.000 to 0.010 inches between the polyiron grooves.

[1]See Exhibit IV for a detailed specification of the assembly procedure.

EXHIBIT 1

Hewlett-Packard Journal

January, 1955

HEWLETT-PACKARD
JOURNAL
TECHNICAL INFORMATION FROM THE -hp- LABORATORIES
Vol. 6 No. 5
PUBLISHED BY THE HEWLETT-PACKARD COMPANY, 275 PAGE MILL ROAD, PALO ALTO, CALIFORNIA
JANUARY, 1955

A Precision Wave Guide Attenuator Which Obeys a Mathematical Law

FOR about a year and a half *-hp-* has been manufacturing a new type of direct-reading precision wave guide attenuator known as a rotary attenuator*. This device is distinguished by the fact that its attenuation follows a predictable, mathematical law not related to frequency. Other than the cutoff attenuator which has several disadvantages in wave guide use, this rotary attenuator is generally considered to be the most accurate attenuator available for wide band microwave applications.

See Also:
"A New Phase Shifter," p. 3

The attenuator has a calibrated range of 0 to 50 db which is accurate within 2% of the db reading at any frequency in a wave guide band. This accuracy is obtained directly from the calibrated dial; no calibration charts are required. The VSWR of the attenuator is less than 1.15 and the insertion loss is less than 1 db.

Until recently, the rotary attenuator has been produced only in 8.2-12.4 kmc size wave guide. It is now being produced in five wave guide sizes which collectively cover the range from 3.95 to 18 kmc.

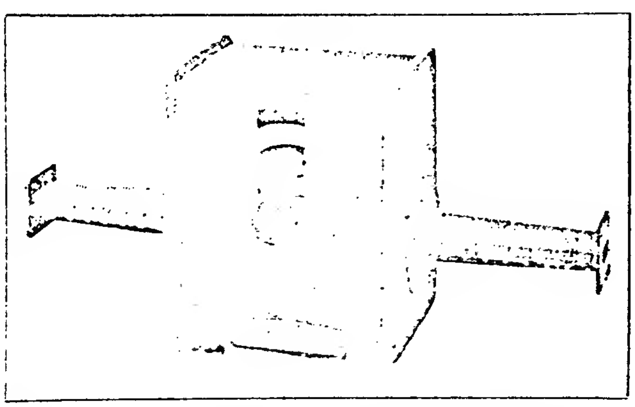


Fig. 1. -hp- Model 382A Variable Attenuator has been designed in five wave guide sizes which collectively cover 3.95 to 18 kmc range. Units are calibrated to 50 db but can usually be used to 70 db.

Basically, the attenuator consists of three sections of wave guide in tandem. In each section a resistive film is placed across the guide as shown in Fig. 2. The middle section is a short length of round guide which is free to rotate axially with respect to the two fixed end sections. The end sections are rectangular-to-round wave guide transitions in which the resistive films are normal to the E field of the applied wave. The construction is symmetrical and the device is bi-directional.

When all films are aligned, the E field of the applied wave is normal to all films. No current then flows in the films, and no attenuation occurs. If the center film is now rotated to some angle θ, the E field can be considered to be split into two components: E sin θ in the plane of the film, and E cos θ at right angles to it. The E sin θ component will be absorbed by the film, while the E cos θ component, oriented at an angle θ with respect to the original wave, will be passed unattenuated to the third section. When it encounters the third film, the E cos θ component will be split into two components. The E cos θ sin θ component will be absorbed, and the E cos^2 θ component will emerge at the same orientation as the original wave.

The attenuation is thus ideally proportional only to the angle to which the center film is rotated and is completely independent of frequency. In db terms the attenuation is equal to 40 log cos θ.

*An attenuator of this type is described by G. C. Southworth, "Principles and Applications of Waveguide Transmission," p. 374, D. Van Nostrand, New York. Inventor of the attenuator is understood to be the late A. E. Bowen.

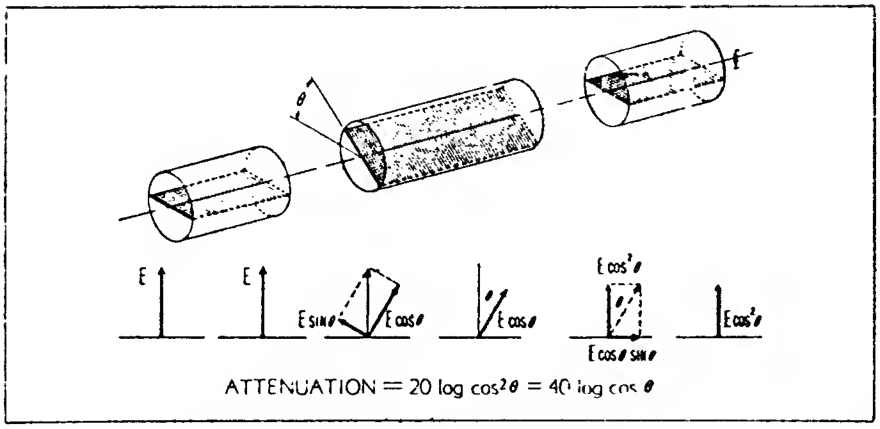


Fig. 2. *Functional drawing indicating operating principle of Model 382A Variable Attenuator.*

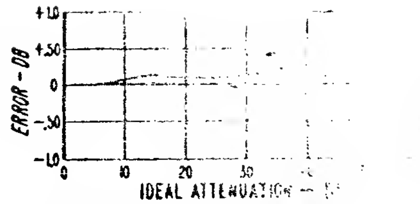


Fig. 3. *Plot of typical max[illegible] countered at any rated freq[illegible] ous attenuation settings.*

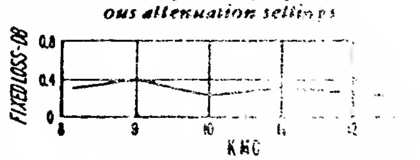


Fig. 4. *Plot of typical inserti[illegible] tained with 8.2-12.4 kmc attenuator [illegible] for zero attenuation.*

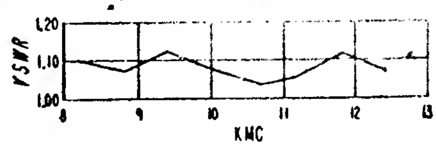


Fig. 5. *Plot of typical VSWR of 8.2-12.4 kmc attenuator.*

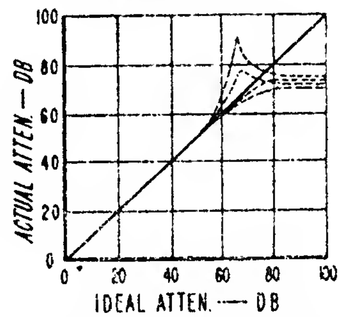


Fig. 6. *Plot of typical attenuation characteristic of rotary attenuator.*

Performance of a typical attenuator in the 8.2-12.4 kmc range is shown in Figs. 3 to 6. Performance of the attenuators in other frequency ranges is comparable. The insertion loss shown in Fig. 4 is the loss encountered with the attenuator set for zero attenuation. Rated value for this loss is 1 db maximum.

Phase shift variations in the attenuator are very small. For settings between 0 and 40 db variations in phase shift are less than one degree. This small value makes the attenuators valuable in applications where it is important that applied power be varied independently of phase. Such requirements occur, for example, in measurements on multi-element antennas where the drive to the various elements must be varied to obtain the desired antenna pattern. By inserting rotary attenuators in series with the appropriate elements, the excitation can be varied over wide ranges.

Since the attenuation is virtually unaffected by frequency, these attenuators, besides being valuable in general-purpose applications, offer a solution to the problem of providing signal generators with precision attenuators at frequencies where cut-off attenuators have excessive slope. By combining two of the attenuators in series, precision attenuations of up to 100 db can be obtained. One or two of the attenuators can also be used with klystron signal sources to form bench type signal generators suitable for many purposes.

Maximum attenuation of the attenuator exceeds the 50 db calibrated range by at least 20 db, but the characteristics in this range are not controlled. Theoretically, the attenuator is capable of very high attenuations. In practice this property is modified by the fact that the resistive film in the middle section can not completely absorb the E sin θ component. Hence, a small leakage component is passed to the output. For high attenuations above 50 db, the leakage component begins to approach the magnitude of the desired output of the attenuator. Ultimate attenuation of the device thus becomes limited by the attenuation of the center rotating film which is 70 db or more. Fig. 6 shows that at 90° rotation the attenuation for any frequency in the rated range is approximately this value.

It is interesting to note that the accuracy of the attenuator does not depend on the stability of the resistive films: as long as their attenuation is high and remains high, performance is not affected. Accurate centering of the films in the guides is obtained by clamping them between machined halves of the guide.

—*B. P. Hand*

SPECIFICATIONS

-hp-

MODEL 382A VARIABLE ATTENUATOR

MODEL:	G382A	J382A	H382A	X382A	P382A
FREQUENCY RANGE (KMC):	3.95-5.85	5.3-8.2	7.0-10.0	8.2-12.4	12.4-18.0
WAVEGUIDE SIZE:	2" x 1"	1½" x ¾"	1¼" x ⅝"	1" x ½"	0.702" x 0.391"
POWER-HANDLING CAPACITY, WATTS, AVERAGE, CONTINUOUS DUTY:	15	10	10	10	5
SIZE, LENGTH:	31⅝"	25"	19⅞"	15½"	12⅛"
HEIGHT:	9¾"	8"	8"	7½"	7¾"
DEPTH:	7-3/16"	6¼"	6¼"	4½"	4½"
WEIGHT, NET:	25	12	10	5	5
SHIPPING:	75	32	30	19	16
PRICE:	$450.00	$300.00	$300.00	$250.00	$250.00

CALIBRATED RANGE: 0 - 50 db.
ACCURACY: ±2% of the reading in db, or 0.1 db, whichever is greater. Includes calibration error plus frequency error.
ATTENUATION AT ZERO SETTING: Less than 1 db. Calibration data available on request.
PHASE SHIFT: Variation less than 1° for all attenuation settings to 40 db.
VSWR: Less than 1.15 entire range of attenuation and frequency.

Prices f.o.b. Palo Alto, California
Data subject to change without notice.

EXHIBIT II ECL 19R

Center Section
Casting Drawing

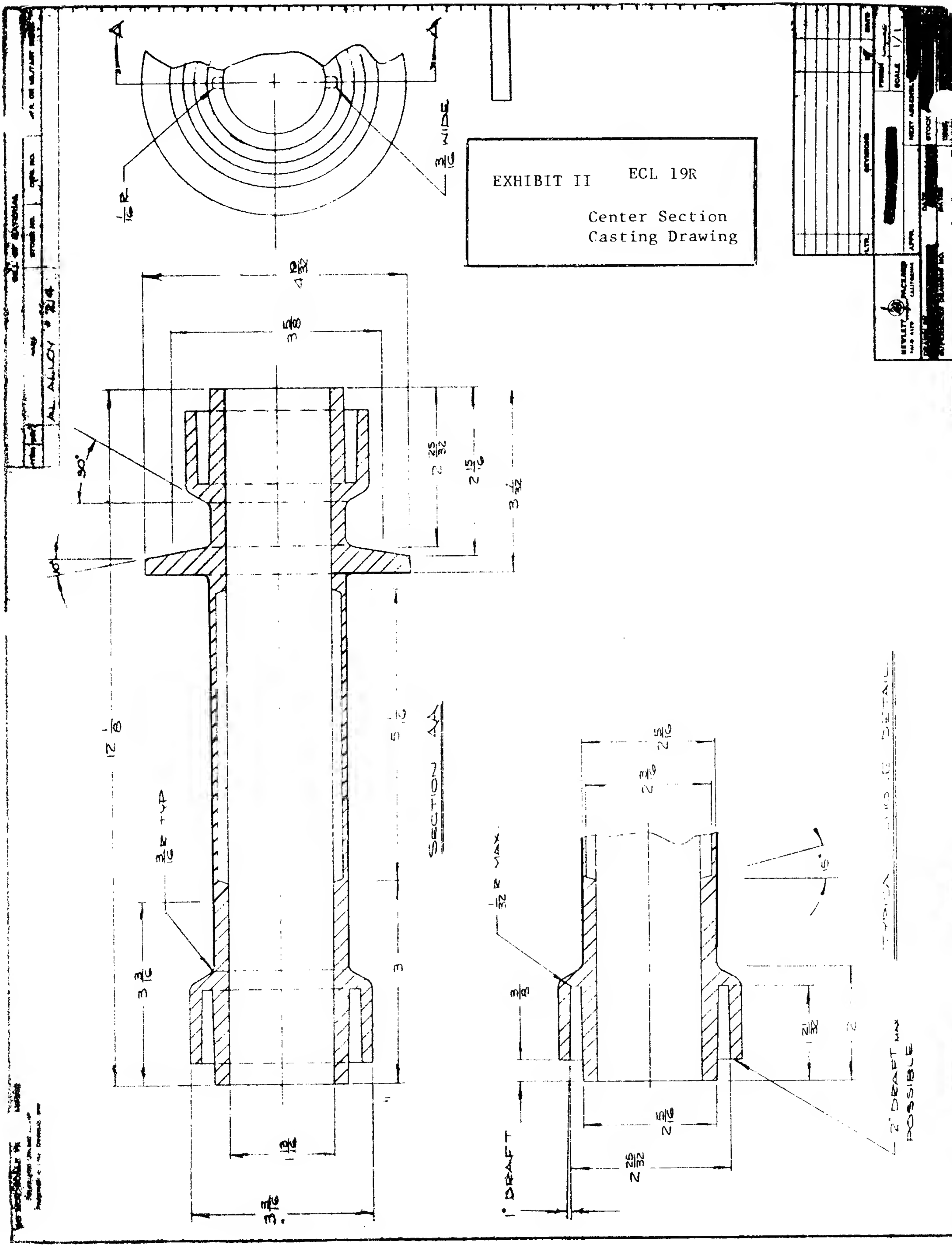


EXHIBIT III

ECL 19R

Center Section
Machining Drawing

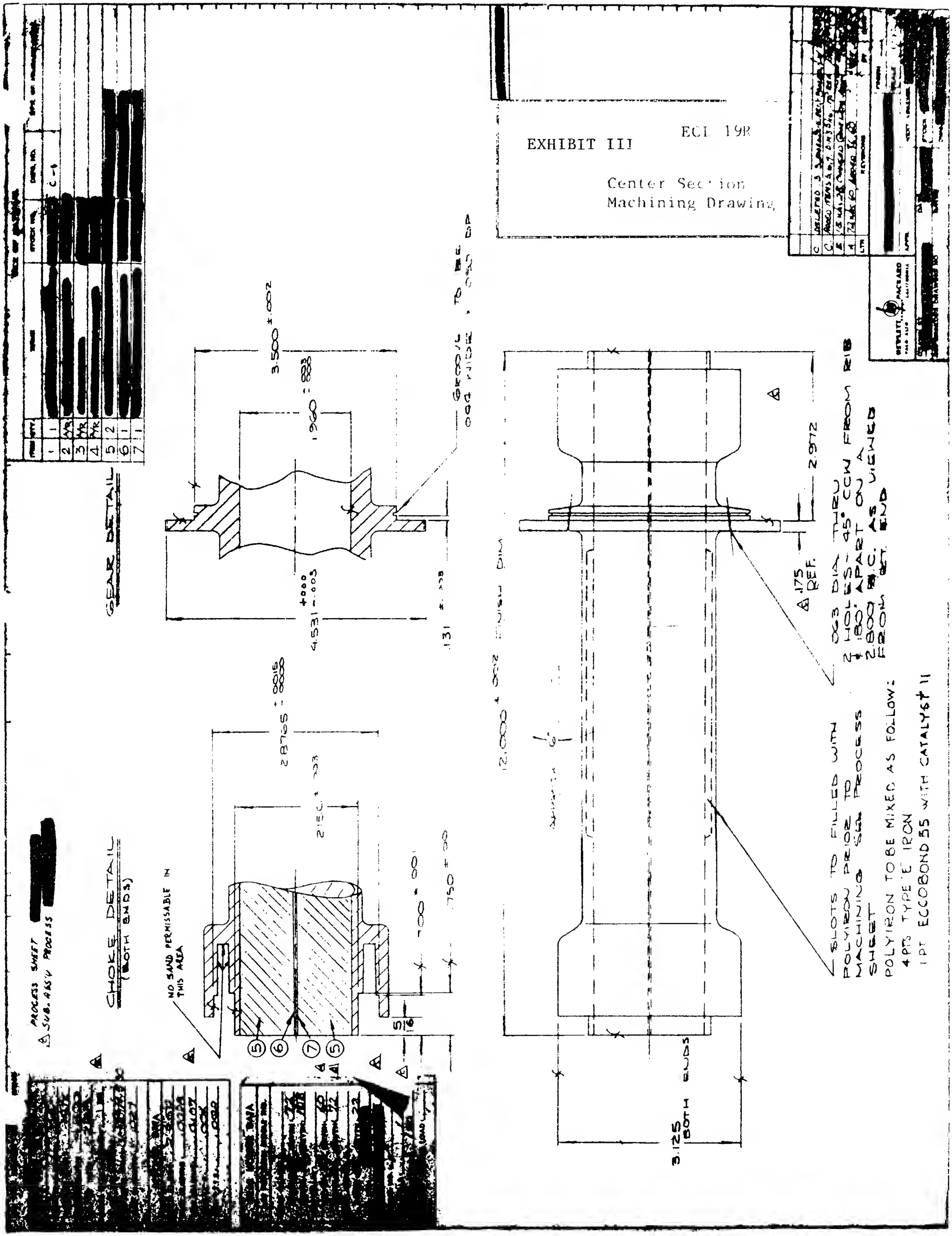


EXHIBIT IV

SUB-ASSEMBLY PROCEDURE

3.3 Maintain liquid level such that plastics are always submerged throughout the entire freezing procedure.

3.4 After approximately 6 minutes (boiling should be at minimum) attempt to place item #3 over insert sub-assembly. If item #3 starts on (do not force), allow it to settle due to its own weight.

If it does not start readily, allow a few more minutes cooling. After item #3 has settled to the bottom, allow a few more minutes in freezing container before removal.

4. Center Section Orientation

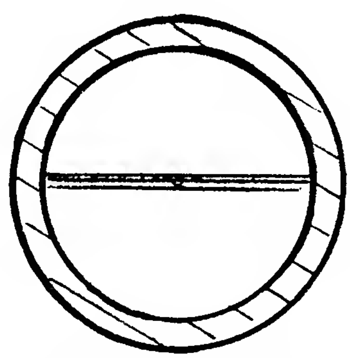
(These steps must be carried out rapidly. Use gloves.)

4.1 Remove entire assembly from freezing container by lifting pulling plate, support by hand during removal.

4.2 Place assembly in vertical position on bench.

4.3 Being careful not to allow inserts to slip from center section, or being splashed with liquid nitrogen that has remained in the chokes, lay entire assembly onto cradle and remove rubber bands.

4.4 Orient plastic inserts such that mica cards are at 90° relative to the ribs on the center section. See Fig. 2. where scribelines show location. Orientation shall not deviate more than 5° from scribeline. Use alignment Wrench [redacted]



4.5 Press inserts back into center section until the sections line up flush on non-stepped end of assembly.

4.6 Allow assembly to return to room temperature.

LTR.	REVISIONS	APPD.	DATE
[redacted]			

TITLE [redacted] SUB-ASSEMBLY PROCEDURE

APPD.

SHEET 2 OF 3

SUPERSEDES

REV.

DWG NO. [redacted]

[redacted] SUB-ASSEMBLY PROCEDURE

1. Visual Inspection

1.1 Visually inspect items #5, 6 for scratches and silver paint continuity on edges.

1.2 Visually inspect items #9. Inspect silver painted surfaces for continuity. (One half of total number of parts should be painted on edges per [redacted].

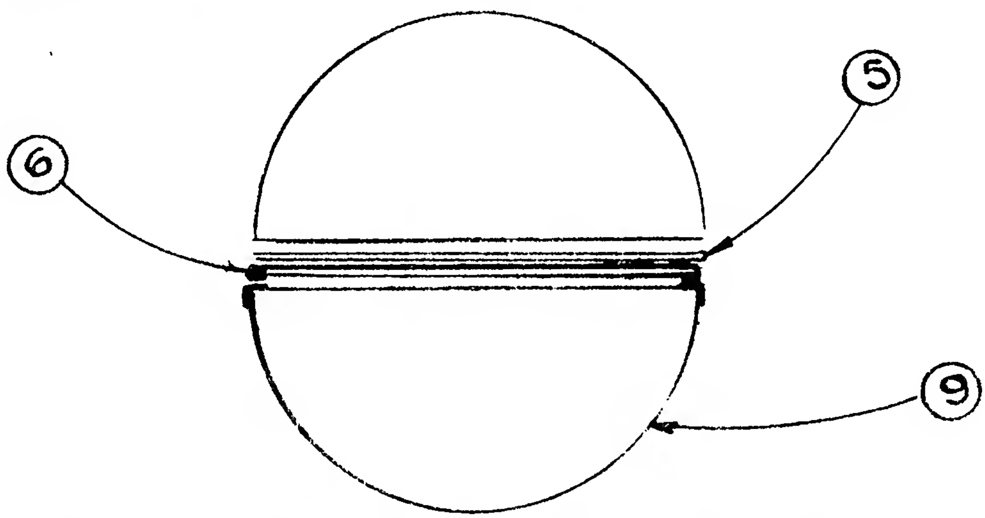
2. Assembly of Inserts

2.1 Place a painted item #9, flat side up, on the bench.

2.2 Place Item #6, film side up, on item #9.

2.3 Place item #5 on item #6.

2.4 Place an unpainted item #9 on item #5.



2.5 Secure the assembly by placing rubber bands around ends and the middle.

3. Freezing (Use extreme caution in this phase of assembly). Always be sure the container is empty before each freezing operation.

3.1 Place insert assembly, stepped end up, on pulling plate, into freezing container. Place cover on container and leave it for 15 minutes to cool.

3.2 Rapidly fill container with liquid nitrogen. Watch boiling.

3.3 Maintain liquid level such that plastics are always submerged throughout the entire freezing procedure.

3.4 After approximately 6 minutes (boiling should be at minimum) attempt to place item #3 over insert sub-assembly. If item #3 starts on (do not force), allow it to settle due to its own weight.

If it does not start readily, allow a few more minutes cooling. After item #3 has settled to the bottom, allow a few more minutes in freezing container before removal.

4. Center Section Orientation

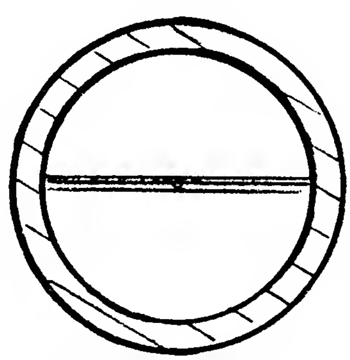
(These steps must be carried out rapidly. Use gloves.)

4.1 Remove entire assembly from freezing container by lifting pulling plate, support by hand during removal.

4.2 Place assembly in vertical position on bench.

4.3 Being careful not to allow inserts to slip from center section, or being splashed with liquid nitrogen that has remained in the chokes, lay entire assembly onto cradle and remove rubber bands.

4.4 Orient plastic inserts such that mica cards are at 90° relative to the ribs on the center section. See Fig. 2. where scribelines show location. Orientation shall not deviate more than 5° from scribeline. Use alignment Wrench [redacted]



4.5 Press inserts back into center section until the sections line up flush on non-stepped end of assembly.

4.6 Allow assembly to return to room temperature.

4.7 Bake assembly for 2 hours in an oven at 50°C.

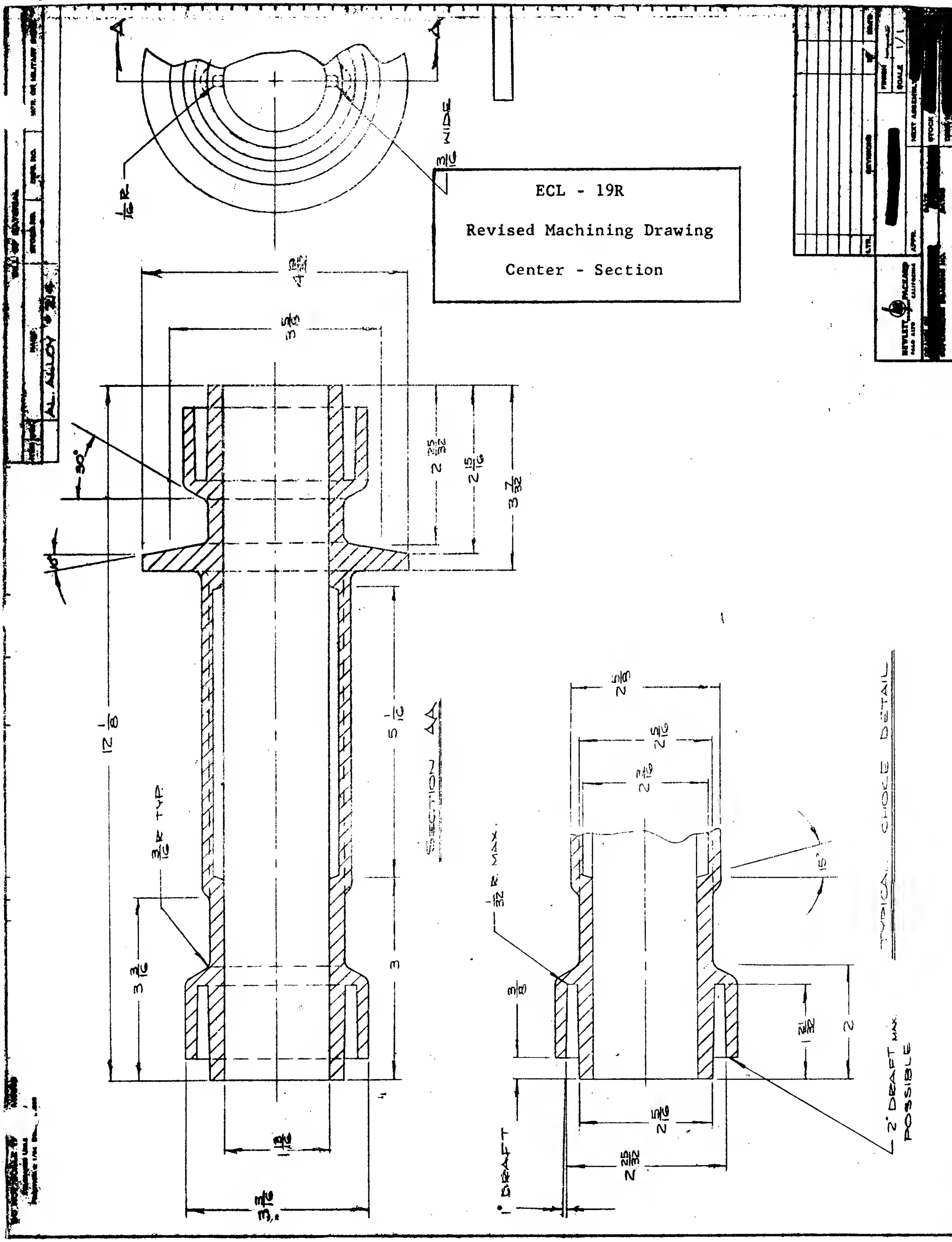
4.8 Let assembly come down to room temperature.

4.9 Send assembly to Department 710.

ECL - 19R

Revised Machining Drawing

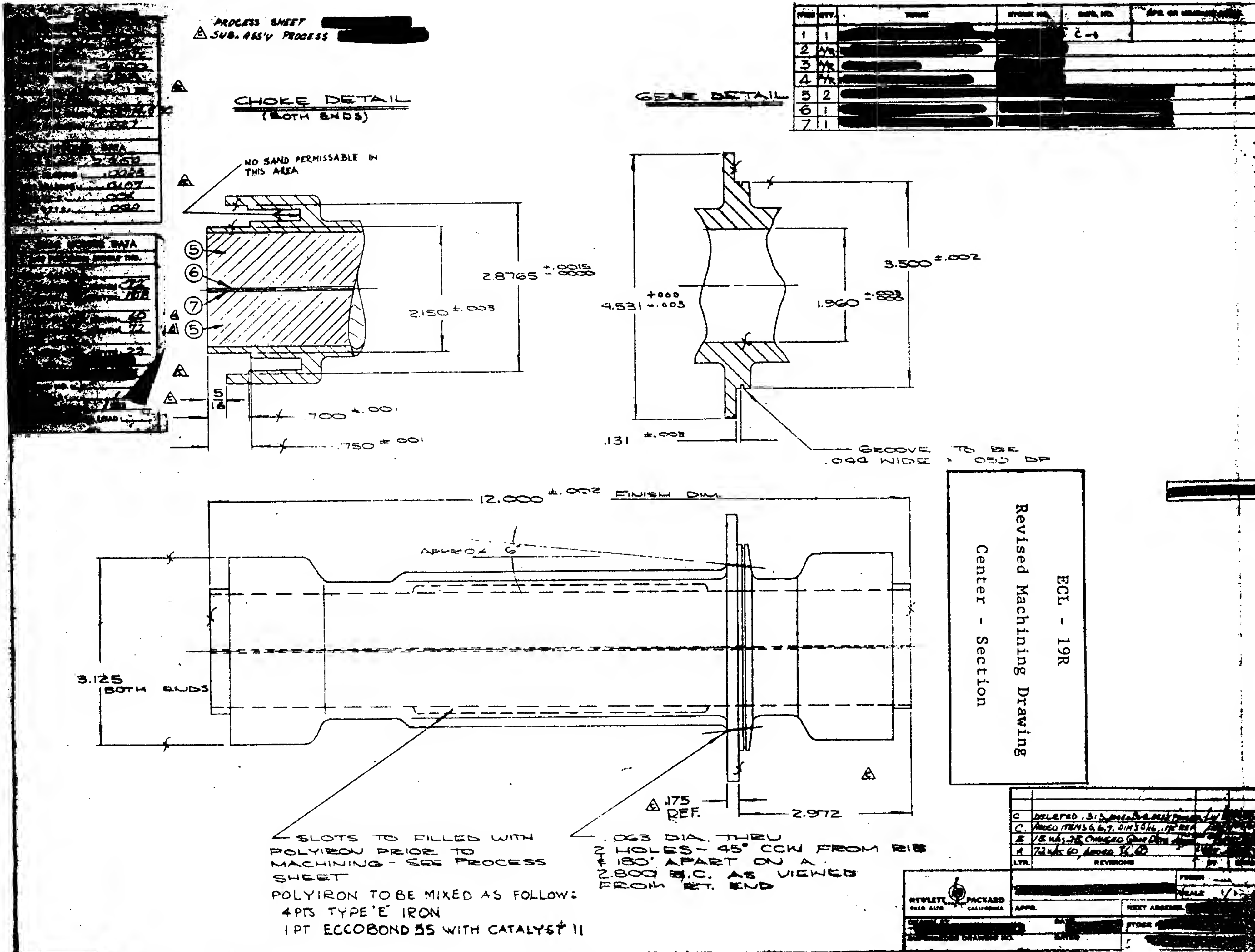
Center - Section



ECL - 19R

Revised Machining Drawing

Center - Section



HEWLETT-PACKARD COMPANY II (B)

During environmental testing, ten prototype assemblies were cooled to -40° C to check for possible changes in alignment caused by core shrinkage. Since maintaining correct calibration depended upon a fixed orientation of the metal film in the bore, misalignment could not be tolerated. During testing the core remained tight.

The castings were then placed in an oven preheated to 75° C. After about twenty minutes they were removed. On each of two of the castings, a large crack along almost the full length of a groove was observed. Maximum crack width was about 1/32".

Faced with this failure in the prototypes, Mr. Adam re-evaluated his project. Thinking over some of the decisions he had made, he still felt that the aluminum alloy used was a good choice. It was inexpensive, not too heavy, had good conductivity, and created no casting problems. The bore size in the casting, however, had been determined by electrical considerations. The thickness of the mica was gauranteed to be between 0.0035 and 0.0055 inches.

Possible Causes of the Cracking

1. Cooling the casting during environmental testing may have introduced residual stresses which weakened the casting along the grooves.

2. The casting may have had intrinsic structural defects due to
   a) inclusions of casting sand, slag, or other foreign materials and
   b) gaseous bubbles and porosity caused by melt metal not being sufficiently degassed before pouring.

3. The choice of materials may have been poor - the aluminum chosen may not have been ductile enough to sustain the strains imposed upon it as the assembly warmed to room temperature.

4. If the tolerances of the core pieces were excessively large, there might have been too much interference at the press fit.

5. Calculations of stress in the groove area, if any were made, may have overlooked the fact that there is an axial component of strain caused by differential thermal expansion in the axial direction.

6. The parts may have been improperly dimensioned, causing too much interference between the core and the housing casting.

7. The polyiron differential expansion between itself and the aluminum may have been substantial. This in itself may have caused excessive strain on the casting.

8. There was undoubtedly a stress concentration in the grooved portion of the casting caused by the reduced section of aluminum there.

9. Cracks and surface imperfections introduced in the casting by machining operations may have caused stess concentrations.

Table I

Properties of Materials Used

ALUMINUM

coefficient of linear expansion: 13×10^{-6} in/in °F^{-1}

$E = 10.3 \times 10^{6}$ lb/in^{2}

ultimate tensile strength: 19×10^{3} to 35×10^{3} lb/in^{2}

PLASTIC CORE (similar to extra high impact polystyrene)

$E = 4.000 \times 10^{5}$ psi

ultimate tensile strength: 5500psi

elongation (in 2") = 15%

coefficient of linear expansion: 62×10^{-6} in/in °F^{-1}

POLYIRON MIXTURE

coefficient of linear expansion: 4 to 5×10^{-5} in/in °F in the range from 80 to 140°F

MICA

coefficient of linear expansion: 18×10^{-6} in/in °F^{-1}

INSTRUCTORS' NOTE

Hewlett-Packard Rotary Vane Wave Attenuator

This case, which describes the cracking of a prototype casting, has been used at Stanford, in a graduate course in analytical design. The case shows that engineers must be careful in selecting problems for analysis, that time pressures can complicate engineering problems, and that engineers need to pay careful attention to detail even in initial design stages.

In the past, the instructor has begun class discussion of the case by asking students whether they think the cracked casting presented a substantial problem to the Hewlett-Packard engineer. After most members of the class agree that this is so, the instructor asks them to suggest some possible causes of the cracking. He lists these on the blackboard. He then discusses each of the suggestions in as much detail as he considers useful. Students are asked which suggestions seem most reasonable. They usually decide that stress concentration at the base of the groove in the casting along with differences in thermal expansion between parts caused deformation and cracking.

Next students are asked to suggest remedies based on this explanation of the cracking. Most students want to analyze loading and stress concentrations. (Here, one can discuss how to calculate stress concentrations along a cast groove and why engineers might calculate stress at all.) The instructor asks students to estimate how much time they would need to do a stress analysis. (Here, one can discuss how to make time estimates.) After convincing themselves that the analysis might well take a week, many students change their minds about making an analysis. At this point in the discussion, the instructor usually presents the Hewlett-Packard engineer's solution: simply thicken the walls of the casting.

A list of possible causes of the cracking and revised drawings are attached.